Nuclear materials

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Major progress has been made in advancing from studies to actions in dealing with nuclear materials. At the same time, the continuously changing nuclear situation provides an impetus for review of nuclear materials stewardship and facilities. As we solve yesterday's problems, new ones emerge. Meeting this challenge requires a technically sound, integrated strategic approach to nuclear materials stewardship. Crosscutting and accessible technical information, analytic tools, and programmatic insights are needed for optimum coordination of nuclear materials stewardship activities.

As great as the problems of nuclear materials management are for the United States, there are both larger and less well-bounded problems internationally. These include not only military nuclear material in the former Soviet Union, but also civilian nuclear material worldwide, and the proliferation risks associated with both. In the former Soviet Union the problems are exacerbated by significant political and economic disruptions. The U.S. practice has been, when confronted with a foreign proliferation or radiological emergency, to take action as needed on a case-by-case basis. In some cases, this has resulted in bringing nuclear material into the United States for disposition. This creates the need for an integrated U.S. approach to nuclear materials stewardship that acknowledges the impact on the United States of these international nuclear materials, and that plans both facilities and processes to accommodate them.

An integrated national approach to nuclear materials stewardship could enhance the ability to (1) conduct nuclear operations more efficiently and (2) provide policy guidance in nuclear material–related matters to meet U.S. national security, energy, and environmental objectives that sometimes conflict. By providing strategic tools that look at the entire system impact, this approach will help make more cost-effective, transparent, and compelling decisions. The Department of Energy (DOE) could take the lead in bringing this new approach into practice.

Historical perspective

About a decade ago, the world order was dominated by two great superpowers with large nuclear arsenals. Only three additional countries had overt nuclear weapons capability. Nuclear power was largely confined to the United States, Western Europe, the Soviet bloc, and Japan. It was managed under the International Atomic Energy Agency's nonproliferation regime. Driven by concerns regarding safety beginning with the 1979 Three Mile Island incident and continuing with the 1986 Chernobyl disaster, nuclear power economics in the United States became increasingly unfavorable. Construction delays increased capital costs, and increasingly stringent safety regulations drove up operations and maintenance costs. However, nuclear power plants were under construction in the United States, and despite the lack of new orders, the return of the nuclear option appeared possible. Passage of legislation governing high-level waste (in

1982 and 1987) and low-level waste (in 1980 and 1985) was perceived to have set the nation on a course toward closure of the nuclear fuel cycle, albeit with direct disposal of spent fuel.

At present, the end of the Cold War has fundamentally altered U.S. defense activities. Production of nuclear-defense fissile material has ceased, and attention has turned to disposition of excess fissile stocks, stockpile stewardship, stabilization and disposal of materials, decontamination and decommissioning of facilities, and environmental cleanup. Diversion prevention has taken center stage, with concern focused on the large quantities of fissile material in an unstable Russia. The number of threshold nuclear weapons states has increased, along with their aggressiveness in attempting to achieve a nuclear weapons capability. There are no nuclear power plants under order or construction in the United States, due to a current economic climate favoring addition of small gas-turbine stations rather than large base-load plants. Both the high-level and low-level waste disposal programs in the United States appear stalled, with an uncertain future. Licensing reforms are in place that might contain capital costs, and the industry has successfully begun to reduce operations and maintenance costs. Yet for the near future, deregulation of the electric power industry may cause a further decline in the number of nuclear plants despite steady improvements in cost and safety.

The same end-of-the-Cold War pressures in the former Soviet Union are resulting in different potential risks for nuclear materials. In addition to the need to dispose of weapons grade materials from dismantlement, Russia and the Ukraine face issues related to continuing production of plutonium (Pu). Also, Russia has not begun the decommissioning and disposal of its weapons complex; therefore, nuclear materials stewardship issues related to that complex process have not yet been addressed.

Outside of the United States, civilian nuclear reactors are being planned, designed, and built. Whereas U.S. projects of nuclear materials from civilian reactors are stable or declining, elsewhere in the world civilian reactor programs are increasing the amount of nuclear materials requiring stewardship. Because of the variety of reactor designs and varying views of plutonium economics, the possible makeup of these materials cannot be anticipated with any degree of certainty. The DOE Energy Information Administration (1996) projects that spent fuel discharge from nuclear power plants will be approximately 10,200–11,499 metric tons (t) per year between 1996 and 2015. The cumulative discharge worldwide of spent nuclear fuel will grow to about 220,000 t in 2015, of which the U.S. share is 40,000 t.

Meeting the challenge

DOE facilities handle a wide variety of nuclear materials. U.S. nuclear materials are used to fuel civilian power reactors and research reactors both domestically and in other countries, to produce various defense-related nuclear materials, and to power naval vessels. Many other valuable nuclear materials are produced in DOE operations, as are a wide variety of wastes containing radioactive components. As a result, the DOE must deal with an extremely complex and dynamic inventory of resources, facilities, and operations in which nuclear materials are created, used, processed, stored, and disposed. Examples of DOE current and future responsibilities include:

- A growing inventory of commercial nuclear power plant spent fuel, currently in excess of 32,000 metric tons
- More than 2 million cubic meters of DOE radioactive wastes, including high-level, low-level, mixed, transuranic, and huge quantities of other, uncharacterized types of wastes
- Hundreds of radioactively contaminated structures, such as reactors, chemical processing facilities, and laboratories
- About 3.7 billion cubic meters of contaminated soil and groundwater at federal nuclear sites and other locations
- More than 600,000 tons of nuclear production materials accumulated to support the nation's civilian and military nuclear programs, including highly enriched uranium (U) and plutonium (Pu)
- About 17,000 nuclear sources used for medicine, waste management, industry, and research
- Fissile material from the former Soviet Union, and foreign research reactor fuel

Nuclear materials issues span three major areas of interest—national security, energy, and environment—as shown in Figure 22-1. Each area has a distinct constituency among the public and in Congress. All three are vital to a safe, secure, healthy, and prosperous future—hence the need to achieve a balanced, coordinated materials management regimen.

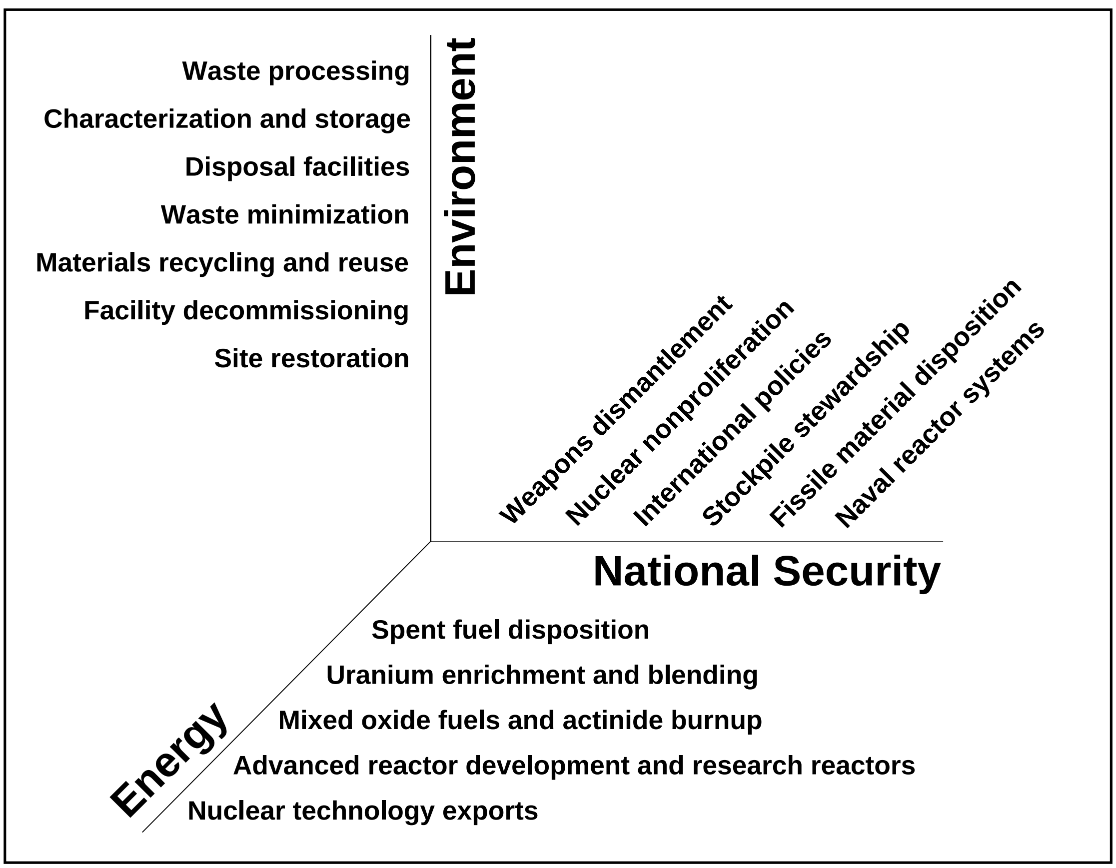

Figure 22-1. Interacting nuclear materials considerations in the areas of energy, environment, and national security.

Each of these missions has complex technical, policy, economic, legal, and political considerations that affect nuclear materials management at both national and international levels. Nuclear operations at DOE facilities have resulted in environmental contamination, forcing programmatic priorities and budget allocations to focus on cleaning up hazards and on modifying continuing operations. In some cases, promises for cleanup have been made that might be difficult (if not impossible) to fulfill, particularly using current technology and projected budgets.

Nuclear materials management is governed by numerous laws, regulations, and regulatory agencies; by DOE's responsibilities to state and other federal agencies; by U.S. cooperation with international organizations; and by U.S. treaty obligations with foreign governments. At least seven major DOE program offices are responsible for various elements of nuclear materials management. Decisions involving individual policies, facilities, or materials are sometimes made without full consideration or knowledge of ripple effects that the decisions trigger.

As we wrestle with the need for new domestic facilities and operations to store, process, transport, and dispose of nuclear materials and nuclear wastes, we are faced with unprecedented technical and nontechnical challenges. At the global level, the dissolution of the Soviet Union has lessened tensions between the United States and its former adversary. As a result, both the United States and Russia are dismantling large numbers of nuclear weapons, producing surpluses of plutonium and enriched uranium. Definitive and technically sound policies and plans for the disposition of these and other materials are urgently needed, both to handle the materials in a safe and environmentally responsible manner and to prevent the proliferation of nuclear weapons and weapon materials.

The U.S. policy of taking foreign nuclear material into U.S. nuclear stewardship has had significant positive effects on world nuclear safety and nonproliferation goals. Examples include weapons-grade material from Kazakstan, highly enriched uranium from Russia, and foreign research reactor spent fuel. The U.S. policy of leadership by example has introduced additional amounts of nuclear material into U.S. nuclear stewardship, for example when the president identified 200 tons of weapons-grade materials as excess to U.S. needs. As the United States develops a robust, comprehensive integrated framework of nuclear materials stewardship, the totality of U.S. environmental and national security interests must be represented. This includes adequate facility capability and policy framework to meet realistic international contingencies and provide policy flexibility for U.S. international leadership.

All of these critical needs must be satisfied as U.S. nuclear hegemony is in decline. Much of the rest of the world is expanding nuclear energy as the United States reduces its role, resulting in less opportunity for the United States to influence their decisions. U.S. commercial nuclear power is declining as a percent of worldwide operating reactors (24.7%) and capacity (28.7%). The United States is now eighteenth out of 30 countries in the world in percent of electrical generation from nuclear reactors (22.5%). The U.S. monopoly on enriched uranium supply has ended, and U.S. nuclear reactor suppliers face intense foreign competition. It seems possible that Sweden will operate its high-level-waste repository before the United States, despite our emphasis on schedule from the start. Virtually all nuclear countries are more advanced in implementing disposition plans for commercial low-level waste than the United States.

Where are we and how did we get there?

In the rush to assign blame for the nuclear materials problems, it is too often forgotten that people made decisions that seemed right in the context of the time. Looking at things in the light of today's knowledge, priorities, and conditions, we see things very differently. For us to deal successfully with many issues, we must look beyond being pro-nuclear or antinuclear to being *about* nuclear. Applying this perspective, let's look at some of today's nuclear materials management issues from the viewpoint of an ideal system that is (1) planned and tested prior to deployment, (2) comprehensive, (3) internally compatible, (4) optimized as a whole, (5) robust, and (6) realistic.

Planned and tested prior to deployment

The essence of systems engineering is to plan and test an entire system prior to deployment. Two conditions prevented this for nuclear materials management in the United States—the conditions under which the nuclear system originated, and the first-of-a-kind nature of the activities.

The system of nuclear materials management in this country was born of necessity during a war of survival. While thousands died daily from international strife, a few gaps in planning did not seem significant. This pressure was relieved by a short post-war pause before nearly four decades of what has been termed a "balance of terror."

Fifty years ago all nuclear activities were pioneering—the first sustained chain reaction at the University of Chicago, the enrichment of U^{235}, the production of plutonium, radiochemical processing, and the Trinity explosion. No systematic cycle through research, development, and pilot plant to production was possible. Plants were under construction before the engineers knew from the scientists what equipment would be installed there.

Beyond these historical factors, many analysts now believe that it is not possible to completely plan a complex new system prior to implementation, and that new systems should be prototyped and significant changes should be expected early and often. Other new technologies have gone through many cycles of change before settling down into a more mature stable phase. From this perspective, significant changes should be expected as a normal part of nuclear materials stewardship. These changes can be managed through information, tools, and insight, and by recognizing adaptability and flexibility as virtues in system approaches.

Comprehensive

Even though the nuclear materials management system may not be fully implemented, it should be comprehensive (in the sense of all-inclusive) with respect to plans and concepts. The most obvious gap is the lack of closure of the nuclear fuel cycle[1]. For commercial power reactors, the fuel cycle has been "closed" several times but reopened by stricter environmental controls or political decisions. These are reasonable responses to changing boundary conditions. On the other hand, it is not reasonable that today, 50 years into the nuclear age, there are still not credible disposal plans for all nuclear waste. Other examples of system incompleteness are the gaps in U.S. nuclear waste classification, the lack of an integrated transportation system, and lack of international considerations in planning.

Lack of credible plans for all waste. The statutory limit of waste loading for Yucca Mountain is 70,000 t of initial heavy metal, which has been allocated by DOE into 63,000 t of commercial reactor spent fuel and 7,000 t of defense waste. However, by the end of the currently planned lifetime of commercial light water reactors, projections are for 84,000 t of spent fuel. About 10,000 t of defense high-level waste and 3000 t of DOE spent fuel are projected. With just these categories totaling nearly 100,000 t, clearly either a second repository will be needed, or the statutory limit at Yucca Mountain raised.

Beyond the statutory-limit issue, there are 256 types of spent fuel alone in the U.S. inventory, and only a few have been analyzed and approved for disposal in the repository. Among other items mentioned (but not planned) for Yucca Mountain are spent naval fuel, plutonium disposition products, depleted uranium, and Greater-than-Class-C low-level waste. The required safety demonstration for these other types could be time-consuming and costly.

Just because a certain waste has a disposition stated in a program plan or environmental impact statement does not mean that the disposition is likely or feasible. For example, there is no certainty that a Yucca Mountain high-level-waste repository will ever open.

Disposal of commercial low-level waste in the United States is stalled by the political process. Only one commercial site is open to most of the country, and the prices have escalated to nearly that of high-level waste on a volumetric basis.

Waste classification gaps. In most nuclear countries, waste is classified by radiation dose level or curie concentration as low-, intermediate-, or high-level. In the United States, low-level waste is defined by curie concentration, and high-level waste is defined by origin. Although the curie concentration of high-level waste is separated from low-level waste implicitly by the current U.S. classification, there are unclear boundaries for other types of waste. There is no clear-cut intermediate classification, although several categories span the gap.

The DOE has defined a category known as TRU waste that contains alpha-emitting radionuclides with an atomic number greater than 92 and half-lives greater than 20 years, at concentrations of transuranic isotopes greater than 100 nanocuries per gram of waste. The Nuclear Regulatory Commission in defining low-level waste established the category known as Greater-than-Class-C, which is defined as having greater than specified limits to radionuclide content measured in Ci/m^3 or nCi/g on a nuclide specific basis. No upper limit is given, and it is only stated that it does not qualify for shallow burial. Because this definition allows the radiation level to be potentially as high as some high-level waste, it is assumed (but not formally required) that Greater-than-Class-C waste will be disposed in a high-level-waste repository. However, from a risk-benefit standpoint this may be unproductive. Likely some Greater-than-Class-C waste should go to a high-level-waste repository, but much should not and the economic penalty is not known.

Another waste classification gap appears for the disposal of plutonium, enriched uranium contaminated with other isotopes, and high fissile content spent fuel. The statutory, regulatory, and programmatic focus of the U.S. high-level-waste repository program is the disposal of high-level defense reprocessing waste and commercial light-water-reactor spent fuel. Yet there are large quantities of plutonium and high fissile content spent fuel that some propose for the repository, largely for nonproliferation reasons. The disposition of contaminated enriched uranium is not even addressed. The repository is not being designed for these materials, which present potential problems in criticality and long-term toxicity.

<u>Lack of an integrated transportation system.</u> In the Swedish nuclear power system, despite having several utilities involved, the fuel cycle was planned as an integrated whole. All power reactors and the spent fuel storage facility are located on the seacoast, so that transportation of fresh and spent fuel is by a specially designed sea transport vessel. The limitations of geography in the United States would not allow all coastal locations, but we have not taken other obvious steps. Not all power reactors are accessible by rail, and not all can accommodate large, cost-effective transport casks.

<u>International considerations in planning.</u> Provisions should be included that allow for the classification of waste from foreign sites, including instances in which the life-history of the materials may not be known. U.S. policy objectives may also be met by encouraging and promoting technology transfer to facilitate foreign nuclear materials stewardship issues. These may be either country specific or regional. In either case, advance planning and long-term resource commitments by the United States are necessary in addition to a robust policy framework and strong technical competencies.

Subsystems compatible

Subsystems should be compatible with each other and the overall system. Although there are many additional components, the three major programs of the DOE nuclear arena were weapons, naval reactors, and civilian reactors. Although U.S. policy from the start has been to have a strong separation between civilian and defense programs, the programs initially operated under parallel but similar policies. That is, all the programs planned to reprocess and recycle the fissionable materials. Waste materials could be handled in a common system. Today we still have a common high-level-waste repository, but the materials from the various programs are dissimilar. To the mix has now been added the possible disposal of excess fissionable materials. It may be necessary to examine the inherited assumption that all high-level waste (including spent fuel) can or should go to the same repository.

Optimized as a whole

Subsystems should not be optimized at the expense of the overall system. For example, for economic reasons, spent naval-reactor fuel is no longer reprocessed. However, spent naval-reactor fuel is highly enriched, and no significant effort has been made to demonstrate that such fuel can meet current repository standards without significant additional conditioning or packaging. By ceasing to reprocess the naval fuel, the fuel subsystem has been economically optimized at the possible expense of the disposal subsystem.

Another example is the excess weapons fissile material. A decision was made to disassemble weapons rapidly and store plutonium prior to disposition, either as parts or some processed form. However, weapons are under very tight controls and accountability, and exist in easily countable form, whereas plutonium becomes more hard to control and account for with each step of processing; therefore more easily a subject for diversion. It has been suggested that the reduction in warheads may have led to an increase in diversion risk.

Robust

The system should be robust enough to survive changing external boundary conditions. Early in the development of the nuclear materials management system, uranium was thought to be a scarce commodity, prices were high, and enrichment was expensive. Therefore, the breeder reactor, which converted abundant U^{238} to plutonium, was thought to be an ideal solution. Similarly, recovery of plutonium from spent light-water-reactor fuel and recycle in MOX (mixed uranium and plutonium oxide) reactors appeared resource-wise and economic. Opposition to these system extensions came almost exclusively from antinuclear activists who were citing weapons proliferation as their main argument. Based on proliferation arguments, a major boundary condition change was made in 1977 when President Carter announced the indefinite deferral of reprocessing in the civilian nuclear sector. Several years later, direct disposal of spent reactor fuel (the once-through cycle) became administrative policy.

Today, uranium is abundant, the price is cheap, and the cost of enrichment has greatly declined. Many regard reprocessing as not cost-effective and spent fuel as a waste rather than a resource. Even highly enriched naval reactor fuel is now in a "once-through" cycle. However, part of the nuclear world continues to treat spent fuel as a resource rather than a waste. France, Germany, Great Britain, Belgium, Russia, and Japan all have their spent fuel reprocessed and either operate, or plan to implement, the MOX fuel cycle.

Politics can affect boundary conditions as strongly as resource availability and economics. Our management of depleted uranium, plutonium, and highly enriched uranium illustrates how nuclear materials management can be an instrument of policy as well as a technical process. Technical optimization needs to be balanced against institutional, economic, and political aspects to reach effective and achievable decisions.

To enhance our nonproliferation objectives, U.S. policy is committed to the once-through fuel cycle, in which there is no reprocessing and the spent fuel is waste. For commercial light water reactors, economics appear to favor the once-through fuel cycle, at least at present and near-future uranium prices. However, the United States has large stocks of depleted uranium, plutonium, and contaminated enriched uranium from reprocessing defense, research, naval, and experimental fuels. These do not readily fit into the planned waste repositories. The enriched material could theoretically be used as fuel, thus gaining some benefit from the already-spent cost of the reprocessing. However, in order to be consistent, the United States is considering as a matter of policy to forego burning these materials in a reactor and attempt direct disposal in order to set a positive example to the rest of the world supportive of nonproliferation. Furthermore, reprocessing future similar spent fuel has been abandoned.[2]

Another example is the lack of spent fuel storage capacity at commercial reactors. Early reactors were designed with limited pool storage capacity for spent fuel because of the regulatory expectation that all spent fuel would be reprocessed. It was even required that the reprocessing waste be solidified within five years. Thus a small pool capacity was a reasonable assumption for designers. Certainly, no one would have planned for life-of-plant storage. All solutions to date (ship to another reactor, ship to an away-from-reactor storage facility such as Morris, rerack the fuel, or move to an onsite, external dry storage) have been ad hoc, with no real national solution. National solutions have been proposed by DOE [monitored retrievable storage facility, multi-purpose (store, transport, dispose) canisters], but not adopted by the country.

Realistic system specifications

As the regulations and policies have evolved, there has been a gradual shift from concern about short-lived radionuclides remaining in high-level waste (and therefore repository performance for a few hundred years), to the long-lived isotopes remaining in spent fuel and repository performance of a million or more years. The degree of protection demanded is neither feasible nor demonstrable. In this case, the unrealistic specifications are imposed from outside the system, as boundary conditions.

Sometimes the system specifications can be technically realistic but unrealistic for nontechnical reasons. This has particularly plagued nuclear materials management. Problems have been approached solely as technical issues, but the resulting technically sound solutions have failed for institutional reasons. Therefore, a successful nuclear materials stewardship system must include nontechnical considerations to be realistic. A good example is the potential high-level-waste repository at Yucca Mountain. Nearly all effort is focused on whether the site is technically acceptable for waste isolation for 10,000 or even a million years, but the extent to which nontechnical issues are integrated into the program is more likely to determine ultimate success than any set of technical data and analyses. Other examples include the low-level-waste site at Ward Valley, which has received a license to operate but is halted by political opposition. The Shoreham nuclear reactor was granted a Nuclear Regulatory Commission license and started low-power operation, but was halted by political considerations.

A possible framework

A national, integrated view would provide significant advantages for managing U.S. nuclear materials. This view can be achieved with information and tools leading to insights that make it possible for DOE, national decision makers, regulators, and commercial providers to take into account all relevant and often competing issues (*e.g.*, technical, legal, regulatory, political, economic, institutional) and systematically identify opportunities, risks, benefits, and costs for various nuclear materials management options.

To achieve such a view, we should begin with a comprehensive, strategic analysis of current locations, quantities, and conditions of nuclear materials nationwide, along with storage, processing, and disposal plans. Specific areas to be examined include the following:

Material regulations and classifications. Examine regulations, classifications, and standards and their impact on nuclear materials management, and develop alternatives for a more consistent, more efficient approach.

Material stocks and flows. Understand what nuclear materials we have, where they are, and where they are going; define gaps and disconnects; and identify technical options, alternatives, and research needs for processing and disposition paths.

Data identification and analysis. Assemble nuclear materials management information and analyze its implications for effective program management and operations, and provide a basis for identifying and resolving policy issues. This information will derive from program plans, records of decision, environmental impact statements, directives and orders, standards and regulations, policies, treaties, inventories, and other such sources.

Information management system. Develop a prototype information management system to help users obtain and understand relevant nuclear materials management information, constraints, and related data, and to provide a basis to optimize management decisions.

Objectives hierarchy. Prepare a hierarchy of objectives that distinguishes high-order goals such as "minimize global nuclear weapons capability," from objectives such as "prevent proliferation of uncontrolled plutonium," from proposed solutions such as "try to prevent all reprocessing." Use this hierarchy and influence diagrams to identify unintended effects of actions taken to satisfy one objective on other objectives.

The payoff

With the technical foundation thus created, we can move toward the development and implementation of a more unified and effective national program for managing the use, storage, processing, and disposal of nuclear materials. Specific benefits include:

- Improved decision making and policy implementation (*i.e.*, greater consistency and more defensible rationale), improved risk management, and lower costs for the management of nuclear materials
- Improved integration and coordination of nuclear material-related activities nation- and agencywide and improved safety, security, and efficiency of nuclear operations
- An information management system, information analysis tools, and technical and nontechnical insights for decision makers, along with a dynamic system to obtain meaningful stakeholder involvement
- Identification of research and development that really makes a difference in providing meaningful nuclear management options, and that provides a basis for use and benefit from advances in the state of the art
- Improved understanding of ramifications and implications of existing and proposed nuclear-material-related policies and regulations

- A strengthening of U.S. security, energy, environmental, and waste-management policies

No single system can capture all the subtleties and complexities of the real world, let alone the many disparate yet legitimate views held among the nuclear community and the nation. But by assembling an agreed-upon, common set of strategic *information*, and a set of *tools* that can be used by all of us, the resulting *insights* from analysis—combined with open and effective communication among us—should result in better understanding, both of the implications of various decisions and the factors that often lead us to differing solutions even when we share common objectives.

Endnotes

1. Closure is here used in the sense of completeness, which would include disposal of spent fuel, not in the sense of implementing a MOX or breeder fuel cycle.
2. It is interesting that where there is a technical imperative, Purex processing continues in the United States. For example, returned foreign research reactor fuel that is aluminum-clad is being processed for safety reasons—it cannot be safely stored until disposal.